Gravitational-Wave Memory: What Spacetime Cannot Forget

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Preface

This document takes a different tack towards communicating science to a non-technical audience. It does so by first presenting a new, creative writing by the author related to gravitational-wave memory. The themes of the writing are subsequently elucidated in a pedagogical text following it. The level of detail provided in the explanatory text is intended to be sufficient for a non-expert to understand the main ideas in the verse. It is not intended to be an exhaustive summary of gravitational-wave memory. Instead, there are references to technical articles and non-technical books where interested readers can pursue the subject in greater detail.

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The transitory and the permanent

I.

I sing of metamorphoses
but not those of Ovid:
less fanciful, yet also stranger.
Empty space, flat, regular,
as far as the eye can see,
and persistent time,
ticking inexorably through the eons,
waiting for news from afar.

II.

It begins almost imperceptibly.
The softest of pushes,
the gentlest of pulls,
dragging objects into motion.
It cannot be evaded,
as space itself is its medium.
Before long, the intensity
and frequency of this distortion builds.
Its source is a force
with the power of myriad suns,
yet the thrashing remains
confined to the subatomic world
and fades with
a dying whisper:
Remember
me
.

III.

The tumult has ended.
No echos, no reverberations,
but space is no longer the same.
Not curved, just distorted
from prior to the convulsions
of space and time.
With each cosmic event
comes a souvenir of waves past
for those sufficiently adept
to find it.

Introduction

The work on the previous page represents some of the key aspects of the gravitational-wave memory effect through both the content of the text and its visual representation. The three stanzas of the poem describe some attributes of space and time before, during, and after the passage of gravitational waves. The indentation of the lines of each stanza has its own significance, which will be described at the end of this work where the relationship between the poem and the physics of the gravitational-wave memory effect will be elaborated upon.

This writing builds on an earlier writing in this series on gravitational waves [1] (which itself built on the first writing on black holes in this series [2]). To make this writing self-contained, a few key aspects of References [1, 2] will be summarized first (though reviewing these previous writings is encouraged). After this review, a brief history of the gravitational-wave memory effect will be discussed and some of the physics underlying the effect will be covered. With this additional background and context, the relationship of introductory poem and the memory effect will be examined.

Review of Black Holes and Gravitational Waves

Black Holes

The first work in this series [2] focused on the surprising properties of the mathematical solution of general relativity corresponding to a non-rotating and unchanging black hole (which as a consequence of its not changing must have existed, and will continue to exist, for all time). It described how the spacetime of such a black hole has a complicated structure that can be described in terms of four different spacetime regions, which were separated by a past and future event horizon (even light rays could not remain within the past horizon, and they could not leave the future horizon). However, the black holes that exist in our Universe are not of this unchanging kind, because they were formed from the collapse of massive stars (see [3] for more details). (There also exist much more massive black holes in the centers of most galaxies, see [4], though this discussion will focus on the black holes ten to a hundred times the mass of the Sun that form from the collapse of stars.) These astrophysical black holes retain a future event horizon (in side of which nothing, not even light can escape), but they no longer have the paradoxical past horizon where no light rays can remain inside.

A large fraction of stars in our (and other) galaxies are orbited by a second star (similar to how the planets orbit the Sun in our Solar System), and the pair of stars is referred to as a "binary star." For example, the nearest star to the Sun, Alpha Centauri, is orbited by two other fainter stars, and the collective system of stars is a stellar triple! Although the collapse of stars to form black holes are some of the most luminous events in the Universe, the second star in a stellar binary can survive this blast. When it does, the resulting system will be a binary composed of a black hole and star. If the second star is sufficiently massive, then it also will eventually collapse to form a black hole. Though this process can take tens of millions of years, it can convert a binary star system into a system of two black holes, which gets called a "binary black hole." Because black holes can be millions of times smaller than the stars that collapsed to form them, the two black holes in the binary can orbit each other, without colliding, on much closer orbits than two stars can. The closer the orbit the higher the speed of the black holes (given that the strength of gravity increases as the separation decreases), and the black-hole speeds eventually approach a significant fraction of the speed of light. This makes them strong sources of gravitational waves, which will be reviewed next.

Gravitational Waves

As discussed in Reference [1], unlike in Newton's theory of gravitation, in general relativity, the gravitational field does not respond instantaneously to changes in the distribution of matter that is generating the corresponding gravitational field. Rather, the changes propagate at the speed of light. In general relativity, the gravitational field is described in terms of the curving of spacetime (the four-dimensional geometry arising from three spatial dimensions and treating time as a fourth dimension on the same footing by using light-travel distances rather than the usual notion of time). The time-dependent spacetime curvature propagates away from the changing distribution of mass at the speed of light in the form of gravitational waves. While ten years passed between Einstein's publication of his theory of special relativity [5] and the general theory [6], within a year of publishing the theory of general relativity, Einstein predicted the existence of gravitational waves [7] (though as discussed in [1] and in more detail in [8], Einstein refined his calculation in a second paper two years later [9]).

Being distortions in spacetime itself, gravitational waves stretch and squeeze all material objects that they encounter. This deformation is what gravitational-wave detectors measure. Given that the intensity of this stretching and squeezing weakens inversely with the distance from the source of the waves, once the waves travel over enormous distances from their extragalactic sources, the waves are extremely small in amplitude. This is one of the reasons that it was only one-hundred years after the prediction of gravitational waves by Einstein, two detectors in the USA known by the acronym LIGO were able to directly measure the stretching and squeezing of spacetime by gravitational waves. The waves that the LIGO detectors observed were consistent with those emitted by a pair of black holes orbiting around each other and then crashing together to form a larger remnant black hole (and the size of the distortions were thousands of times smaller than the size of a proton). The properties of the gravitational waves emitted by these binary black hole systems will be reviewed next.

Gravitational Waves Generated by Pairs of Black Holes

The gravitational waves from the binary black hole system were just described as undergoing a sequence of stages: an orbital phase, a collisional phase, and a settling phase to a final remnant black hole. This three-step sequence is often described in just three words: inspiral, merger, and ringdown. The poem in [1] and the second stanza of the poem in this writing focus on how the gravitational waves behave during these three stages.

The inspiral phase is the longest lasting. In Newtonian gravity, two astronomical bodies can orbit around each other indefinitely (and Newton's theory of gravity predicts that the shape of the orbit will be an ellipse). However, in general relativity, gravitational waves are emitted from such a binary system (primarily at twice the orbital frequency). Gravitational-waves carry energy away from the binary (as predicted in Einstein's 1918 paper [9]), and that loss of energy causes the objects in the binary to orbit more closely. The gravitational-waves are emitted at a slightly higher frequency, which causes the amount of gravitational-wave energy to increase. This is an unstable process (the orbital frequency continues increasing and the gravitational waves become stronger) which only terminates when the objects in the binary crash into each other.

For two black holes, this collision is referred to as the merger phase, during which the energy carried away by the gravitational waves peaks, and the two black holes combine to form a more massive black hole. When the remnant black hole after the collision first forms from the two individual black holes, its event horizon at that instant has a highly distorted shape (unlike the spherical or ellipsoidal shape of an isolated black hole's event horizon at a given moment in time). This configuration is not stable, and the highly distorted black hole settles into the ellipsoidal shape rapidly. Because this has the same qualitative features of the decaying amplitude tone of a struck bell, it has been called the ringdown phase of this process.

The gravitational-wave energy emitted throughout these three stages of inspiral, merger, and ringdown have other surprising consequences, which are referred to as the gravitational-wave memory effect. These will be discussed in more detail next.

Gravitational-Wave Memory

The historical context for the computation of the memory effect

The effect now known as the gravitational-wave memory effect was originally predicted in a different context than the inspiral, merger, and ringdown of a binary black hole system described above. According to the introduction to a recent journal article [10], the first calculation of the memory effect was inspired by an early claimed detection of gravitational waves by Joseph Weber in 1969 [11]. This claimed detection was unable to be reproduced independently, which led to its being discredited (as was discussed in the other writing in [1]), but it inspired theoretical astrophysicists to propose possible sources of gravitational waves that could account for the large amplitude of the claimed gravitational-wave detections by Weber. Unlike the binary black holes observed by LIGO, which are located billions of light-years away from the Earth (extragalactic), the sources of gravitational waves like those Weber claimed to observe would most likely need to be coming from the Milky Way galaxy.

In the center of our galaxy, there is a "supermassive" black hole that weighs several million times the mass of our Sun. The strong pull of this black hole brings smaller stellar-mass black holes close to it, which allows for encounters between the lighter stellar-mass black holes to occur as they orbit rapidly around the massive black hole. On rare occasions, as two lighter black holes gravitationally attract the other as they undergo a close encounter, which will produce a strong gravitational deflection of the trajectories of the black holes. It was this type of deflection, or gravitational scattering problem, that two physicists in the U.S.S.R., Yakov Zeldovich and Alexander Polnarev [12], calculated to try to understand Weber's claimed detection of gravitational waves. They computed the gravitational waves emitted during this process and found a surprising result. To describe it, a brief review of how gravitational waves affect a detector is helpful.

The Physical Effects of Gravitational Waves

There are two ways of describing the stretching and squeezing effects on spacetime that occur as a gravitational wave passes by the LIGO detectors. The first is in terms of the curvature of spacetime. Spacetime curvature is closely related to the relative acceleration that objects in free fall experience when they fall in a non-uniform gravitational field. These effects of spacetime curvature arise even in Newtonian gravity, the most familiar example of which is the ocean tides raised on the Earth by the Moon. The Moon's gravitation pull is not uniform on the Earth, because the gravitational pull of the Moon falls off inversely with the square of the distance from its center, and the Earth has a sufficiently large size that the pull on the Earth's far and near sides differ from that on its center. This phenomenon raises tidal bulges in the oceans, because the water on the side nearest to the Moon gets a stronger pull than the Earth's center, which has a stronger pull than the water on the far side of the Earth. The Moon's orbital period around the Earth is about four weeks, so the changing location of the two high and low tides arise primarily from the rotation of the Earth as the Moon's position stays approximately fixed in the sky.

Gravitational waves produce a similar relative acceleration of the mirrors at the end of each arm of the LIGO detectors from the shared source of laser light that bounces off of the mirrors (which is how the length of the arms of LIGO are measured). One way of understanding the measurement made by the LIGO detectors is that they are sensing these extremely small accelerations. Unlike the example of the tides, the gravitational waves from the mergers of black holes are oscillating hundreds to a thousand times a second. This allows them to be distinguished more easily from other gravitating objects (though also introduces challenges to distinguish them from objects on Earth that mechanically vibrate the detectors at these frequencies!).

The second way to understand the detection of gravitational-waves is by setting up well-behaved coordinates and measuring the change in length of the arms of the LIGO detector as a gravitational-wave passes by. While measuring the distance would contain equivalent information to the measurement of relative acceleration described above, it has additional challenges: specifically, there is more freedom in terms of how one defines the coordinates in the measurement of length. The freedom in defining coordinates is an inherent feature in general relativity (that no coordinate system should be preferred), but it also introduces a potential ambiguity when coordinates are used to interpret the results of gravitational experiments. For example, one can use curved coordinates in a space that is flat, or locally flat coordinates in a space that is curved (meaning that there are rectilinear coordinates where the distance between points is measured in the typical approach used in flat space).

The Physical Effects of the Gravitational-Wave Memory

We can now return to the intriguing result computed by Zeldovich and Polnarev. When the black holes are very far away from each other and moving on nearly straight-line trajectories, they produce almost no gravitational waves, because their motion has no significant difference from inertial motion in flat space. It is natural to describe their positions in flat, rectilinear coordinates. While the space is curved close to the black holes, at distances far from the black holes, space approaches being flat. As the black holes make their closest approach, they rapidly change direction, and in this process, they curve space not only close to their locations, but also through a burst of gravitational waves that gets emitted in this process. Much later, the black holes fly off on roughly straight-line trajectories again, in different directions from where they entered. The space is not curved by the gravitational waves any longer, and one might expect the coordinates to be restored the flat, uncurved coordinates used before the black holes' close encounter. However, Zeldovich and Polnarev found that the coordinates were distorted in a static (unchanging with time) manner!

Typically, a static change in the coordinates can be removed by an appropriate redefinition of the unit of length. In this case, however, doing so would also change the standards used for measuring distances before the burst of waves, which would then be distorted. Thus, there is coordinate-invariant information in the fact that the conventions for measuring distances in the usual ways in the flat spaces before and after the waves pass are different. This change is what later was referred to as the gravitational-wave memory effect.

Its effect on the detectors can also be understood through the relative acceleration induced by the spacetime curvature of the gravitational waves far from the two black holes. Unless the relative acceleration of the ends of the detector is highly symmetrical, the integrated effect of the acceleration on the position of the ends of the detector will differ before and after the burst of gravitational waves. For an idealized detector that experiences no other forces (or accelerations) besides those of the gravitational waves, the detector will be slightly distorted (its ends will be displaced) by the cumulative effects of the gravitational waves. This distortion or displacement is an alternate way of understanding a physical effect related to the memory that can be measured.

This alternate explanation in terms of relative acceleration hints at one of the challenges of detecting the memory effect, because it assumed that the detector experienced no other external forces that could shift the positions of the detector. It is not possible to eliminate the effects of such external forces indefinitely, so eventually the motion induced by other forces can mask the effects of the displacement from the memory effect (in a kind of gravitational-wave memory loss). This challenge can be avoided by taking measurements over shorter times and measuring the accumulation of the lasting offset as a function of time rather than the lasting offset itself.

The particular source of gravitational-wave memory considered by Zeldovich and Polnarev also requires that the black holes must pass each other at extremely short distances and at velocities near the speed of light in these fly-by encounters to produce gravitational-waves strong enough that the LIGO detectors can measure them. Unfortunately, such encounters are likely to be very rare, and unlike to happen while the detectors are operating. Thus, other gravitational-wave sources besides black-hole fly-by encounters will be required to observe the memory effect. It has been shown that such astrophysical sources that produce memory effects more frequently exist, and we describe them next.

Further History of the Gravitational-Wave Memory Effect

Several years later, a different astrophysical source of the gravitational-wave memory effect was predicted in two independent theoretical calculations in the same year by Ruben Epstein [13] and Michael Turner [14]. Epstein and Turner calculated the gravitational-wave signal that is produced during the collapse of a massive star to form a neutron star or a black hole. The relativistic motion of the stellar matter during the collapse contributes to the gravitational waves, but it is not the only contribution. During the supernova, new atomic elements are formed in the extreme heat of the supernova explosion, and in the process, a very high luminosity of nearly massless particles known as neutrinos, are also generated. The neutrinos carry away most of the energy away from the supernova, and they do so at nearly the speed of light, given that the energy of the neutrinos created is much higher than their rest-mass energy.

An interesting property of the gravitational waves generated by the neutrinos is that they depend on the asymmetry in the power radiated in neutrinos that is integrated in time over the entire burst of neutrinos passing by the GW detector. This integrated effect generically leads to a lasting offset in the amplitude of the gravitational waves, which is precisely what is responsible for producing the memory effect. Supernova occur frequently throughout the entire universe, but gravitational waves from a supernova will likely be able to be measured only if the star explodes in our galaxy. Given that the rate of supernova explosions is about once per century in the Milky Way, the chances of measuring the memory effect from a supernova is better than that of a black-hole fly-by encounter, but it still a potentially long waiting time for a human lifespan.

When binary black holes inspiral and merge, the gravitational waves carry away energy from the binary (as noted above). Remarkably, the peak power emitted in gravitational waves can be thousands of times higher than the peak luminosity emitted in neutrinos during a supernova. The gravitational-wave power is also radiated asymmetrically, and like the power radiated in neutrinos in a supernova, it will produce gravitational waves. This was first predicted over a decade later in a mathematical paper by Demetrios Christodoulou [15], though this more physical explanation was given shortly after in a paper by Kip Thorne [16]. The effect has subsequently been called the Christodoulou (and also the nonlinear) memory effect. Like the neutrino-produced gravitational-wave memory, the Christodoulou memory is an effect that depends on the integrated power in gravitational waves, but given that this power can be thousands of times larger, it could be measured from extragalactic sources.

Unfortunately, the amplitude of the Christodoulou memory is smaller (and lower in frequency) than the primary gravitational waves that LIGO has measured. This makes it too weak for current gravitational-wave detectors to confidently observe from an individual binary black hole system. There are statistical methods that can be applied to look for the weak memory signals, across many different observations of binary black hole mergers, each of which is hidden below the level of the detector noise. When LIGO detects thousands of black hole mergers, it has been simulated that LIGO will be able to see evidence for the presence of the memory effect in the thousands of detections; currently, the hundreds of black hole mergers measured to date are insufficient to provide confident evidence for the gravitational-wave memory effect.

Explanation of the Poem

The poem reflects upon the properties of empty, flat space before gravitational waves arrive (in the first stanza), how space curves while gravitational waves from a binary black hole system are passing by a detector (the second stanza), and finally, how the gravitational-wave memory effect changes space after the waves have passed by the detector (the third stanza). The indentation of the lines mimics the time dependence of the change in length of one of the arms of the LIGO detector as a gravitational wave passes by, the specifics of which will be described in more detail below.

The first stanza describes the times before the first detectable gravitational waves reach the detector, when spacetime is flat (no curvature), and methods for measuring distances and elapsed times are independent of space and time. The indentation of the lines are aligned, which aims to represent these uniform length and time standards throughout space when no gravitational waves are passing by the detector. There is no advanced warning that the waves are coming (they travel at the speed of light, and nothing can move faster locally than the speed of light), so gravitational-wave detectors need to wait in a state ready to detect an incoming wave at any time, from any direction. This is the figurative news referred to, though the time derivative of the gravitational waves is called the news (making it both literal and figurative).

The second stanza describes the stretching and squeezing of space that occurs as the gravitational wave pass by the detector. The amount of left or right indentation from the first stanza represents the stretching or squeezing effect, and the change moving from line to line represents its time dependence. During the early stages of a black hole merger, the orbital period of the black holes is lowest, and the gravitational waves similarly vary slowly and have smaller amplitude oscillations. Because the power contained in the gravitational waves is also lower, very little shift in the average value of the oscillations has accumulated. Thus, the gravitational waves induce almost periodic oscillations in length in the detector arms about the reference length before the waves arrived. However, the orbital period becomes shorter as the inspiral progresses, and this produces larger amplitude waves with a higher frequency, and an increase in the growing displacement from the early-time reference length. The gravitational waves (and the rate of accumulation of the lasting offset) peak as the black holes plunge towards each other and merge to form a distorted remnant black hole. The distorted remnant black hole quickly settles to a steadily rotating black hole, and in this process gravitational waves have a nearly fixed frequency, but they rapidly decay in amplitude. What remains after this decay is the lasting, static offset in the length of the detector.

The final stanza reflects this final state after the waves have passed. There is a uniform larger indentation from the first stanza, because space is again flat (not curved as when the waves pass by) but lengths are distorted from those used before the gravitational waves arrived. This change in distances is the souvenir of the waves past that persists after they have traveled beyond the detector. It is challenging to measure this lasting strain, not only because it is typically smaller in amplitude than the primary gravitational waves described in the second stanza, but also for more technical experimental reasons in how LIGO makes its measurements of gravitational waves. Because of the large number of random mechanical vibrations that disrupt the sensitive distance measurements LIGO makes, it must frequently recalibrate the lengths of the arms and shift them back to their original positions. Thus, all LIGO can measure in practice is the slow accumulation of the memory effect while the waves are passing rather than the persistent offset. However, the adept LIGO data analysts are searching precisely for the presence of this effect to uncover this surprising prediction of Einstein's general relativity.

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